THE SOUTHWESTERN NATURALIST 16(3&4):387–401 FEB. 18, 1972

TOPOGRAPHIC RELATIONS OF VEGETATION AND SOIL IN A SOUTHEASTERN ARIZONA GRASSLAND[1]

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ABSTRACT. Variation in plant cover with aspect, slope position, and soil attributes was investigated on grasslands in the Walnut Gulch Experimental Watershed in southeastern Arizona. Two plant communities were defined, based upon coefficients of interspecific association among 11 species. The *Bouteloua eriopoda* (black grama) community was found primarily on SW to SE aspects, Hathaway soils and upper slopes with soil attributes of relatively low moisture retention, organic carbon and clay content, but high pH, sand and gravel content. The *Hilaria belangeri* (curly mesquite) community was found primarily on NW to NE aspects, Bernardino soils and lower slopes with soil attributes the converse of the other community. *H. belangeri* appears to be limited in its distribution on SW to SE aspects because the greater solar irradiation on these aspects, at other than the 2- to 3-month summer growing season, causes drought conditions which reach critical proportions sooner in the arid spring or fall.

The effect of topography on vegetation and microclimate has been investigated extensively, particularly with reference to north and south aspects. Less attention has been given to topographic variation of quantitative soil attributes.

The primary objective of this investigation was to determine the relationship of vegetation to aspect, slope position, and soil attributes.

The equation

$$v,s = f(cl, o, r, p, t)$$

has been suggested (Major, 1951; Jenny, 1941, 1958) to describe vegetation (v) and soil (s) parameters at the time of initial development as a function of the independent variables climate (cl), organisms (o), relief (r), parent material (p), and time (t).

Although this equation is useful in forming an approach to an investigation, the independent variables may not be ecologically inde-

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pendent (Billings, 1952) and the complete equation is insoluble because precise quantitative values cannot be assigned to all terms (Daubenmire, 1968). In the present investigation, certain soil variables may be considered primarily as independent or dependent variables depending upon the approach. Previous soil development was undoubtedly a factor in formation of the present vegetation at the study site, and in this sense soil may be considered primarily an independent variable. In historical terms, however, and in this investigation, both vegetation and soil parameters are dependent variables as given in the above equation.

Vegetation and soil variables are primarily a function of relief or parent material if all other factors in the equation are held essentially constant. In this investigation, climate, organisms, time, and slope are considered to be controlled to the extent that their influence on the dependent variable is insignificant.

STUDY AREA. Typical physiography in southeastern Arizona consists of isolated mountain blocks separated by broad alluvial basins. The study area is part of the 150-km² Walnut Gulch Experimental Watershed surrounding Tombstone, Arizona, elevation 1392 m. On the west, the topographic relief of the Tombstone Hills results from great thicknesses of sedimentary rocks, mostly limestone, which are underlain by, and adjacent to, large Tertiary igneous bodies. The lower Dragoon Mountains on the east are igneous, without caprock, and of Triassic-Jurassic age (Spangler and Libby, 1968) (Fig. 1).

Climatic records from Tombstone over a 60-year period indicate an average annual precipitation of about 358 mm, although a recent 11-year record (1955–1965) indicates an annual average of 285 mm (Osborn and Hickok, 1968). Approximately 70% falls from July through September and most of the remainder from December through March. An arid season occurs in spring and another, less intense, in the fall. Summer precipitation in July and August is generally from the Gulf of Mexico, brought by upper air circulation around the west end of the Bermuda High (Bryson and Lowry, 1955). In September, precipitation is generally from west-coast tropical cyclones (Hastings and Turner, 1965). Winter precipitation generally results from a migratory low pressure system moving in from the Pacific Ocean.

Watershed records indicate that winter precipitation is less reliable than summer precipitation for the season, a phenomenon found to occur elsewhere in southern Arizona (McDonald, 1956). Although winter precipitation is less reliable, individual storms provide more uniform, low-intensity distribution when they occur over the area. Summer storms are generally not uniformly distributed and characteristically have maximum intensities of from 5 to 10 inches per hour. Duration of summer storms may be only a few minutes and is rarely more than 60 minutes.

Two general locations, approximately 4 km apart and in areas mapped as different soil series, were located on alluvial slopes in the upper part of the watershed. In most cases, directly opposing aspects were sampled from the same hill, with all six study aspects represented at each location. Parent materials of mixed mineralogy originally differed chiefly in lime content and gave rise to a different soil series at

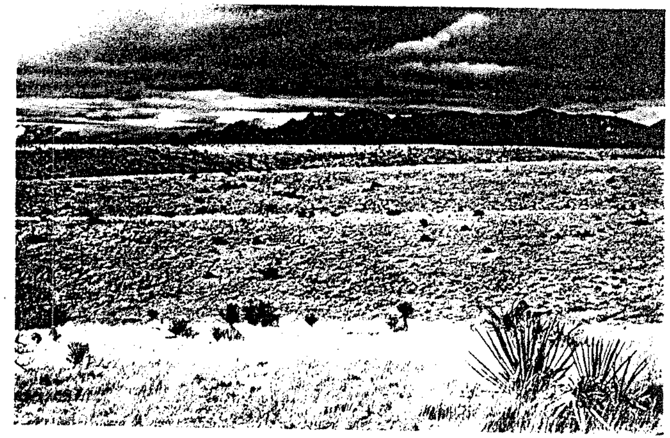


Fig. 1. Representative study slopes in the Hathaway soil study location looking north toward a segment of the Dragoon Mountains. *Yucca elata* is the preponderant shrub.

each of the two locations. If sufficient lime was present throughout the profile, still unleached so that free $CaCO_3$ was in the A horizons, the soil was named Hathaway. If $CaCO_3$ was low enough to allow leaching to a C horizon, the soil was named Bernardino. Low $CaCO_3$ also results in a stronger clay in the B horizon and incomplete base saturation in the A horizon (Soil Conservation Service, 1967).

Vegetation of the area is shortgrass or grass-scrub which has conventionally been included in the Desert-Grassland Transition (Shreve, 1942). The study area is presently grazed and has a history of grazing activity, although the history is less well known before 1900 than after that date. There were two general periods of grazing activity in southeastern Arizona, from 1700 to 1822 and from 1872 to present (Wagoner, 1952). The first period resulted from an influx of Spanish and Mexican cattle while the second period involved mostly Anglos. The intervening years of less intense grazing were partially the result of raids by Apaches. The second grazing period was stimulated by the cessation of raids in 1886 and the building of the railroads. The largest ranch in what was then Sonora was described in 1851 as having more than 40,000 cattle roaming the length of the nearby Babocomari Valley, but an 1870 census found about 5,100 cattle in Arizona (Wagoner, 1952). Arizona lands carried over 800,000 cattle and were overgrazed by the early 1890's when detrimental conditions for plants and cattle were intensified by severe drought. Cattle numbers declined until 1900 when about 360,000 remained (Thornber, 1910). Grazing pressures increased on the study area after 1900, reached a peak in the late 1920's, and continued heavy until 1938. According to Charles M. Kendall, Tombstone area rancher, grazing has been moderate since 1938, i.e. 10 to 12 animals per section per year.

METHODS. Vegetation was sampled with 30 line intercepts on two soil series and six aspects (NW, N, NE, SE, S, SW). Exposures on the E and W were rarely found and were not included in the investigation. Each line intercept was 30 m in length with 3-m frequency intervals. Line intercept was measured as basal area for grasses and as crown cover for shrubs and forbs.

The following were criteria for 20 study slopes where the 30 line intercepts were obtained:

(1) Slopes presenting essentially one aspect with homogeneous microtopography;
(2) Slopes in a range of steepness from 13 to 25%.

At 10 of the 20 study slopes, where steepness from top to bottom varied less than 5%, two line intercepts were obtained. One line intercept was located approximately 20 m from the top and the other about 15 m from the bottom. The distance between the lower line intercepts and the top of the slope averaged almost 50 m. On each of the remaining 10 study slopes, only one line intercept, about 20 m from the top, was obtained. All line intercepts were laid out with a steel tape perpendicular to the slope. Aspect and slope were determined with a magnetic compass and an Abney level, respectively. The slopes studied had average gradients of 16.8%, and although the range was from 13 to 25%, south exposures averaged merely 0.2% less slope than north exposures.

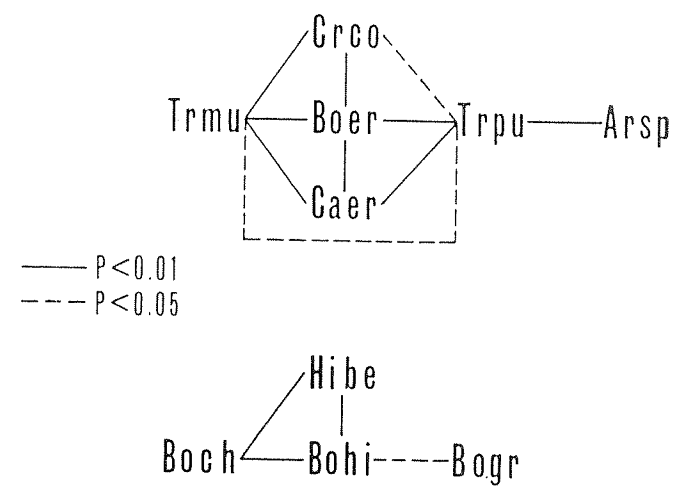
Two types of soil samples were obtained within the first, fifth, and tenth 3-m interval on each transect. A crustal soil sample including approximately the upper 0.5 cm was obtained with a flat hand trowel. A soil sample from the 0- to 15-cm layer was obtained with a soil auger.

Determinations were made from soil samples for percent gravel and for the fraction smaller than 2 mm after the soils were dispersed in a shaker and mortar and pestle.

Laboratory determinations on soil fractions smaller than 2 mm were made for: (1) moisture retention at 15-atm tension; (2) nitrate, by phenol disulfonic; (3) organic carbon, by a wet digestion with potassium dichromate; (4) pH, by a glass electrode; and (5) sand, silt, and clay, by hydrometer. All laboratory determinations follow procedures outlined in Black (1965).

RESULTS AND DISCUSSION. VEGETATION: Presence data from 300 line intercepts were utilized to obtain a coefficient of interspecific association (Cole, 1949; Hurlbert, 1969) for each possible pairing of 11 major species. Species which occurred in less than 10% of the line intercepts were excluded. All species are perennial grasses except for the small perennial shrub *Calliandra eriophylla* Benth. (fairy-duster) and the suffruticose *Croton corymbulosus* Engelm. Two different plant communities occur in the study area (Fig. 2). Only *Bouteloua curtipendula* (Michx.) Torr. (side-oats grama) failed to show a significant positive association with another species.

Grass cover on NW to NE aspects (14.9%) was greater than on SE to SW aspects (10.9%), although there was considerably less difference in total cover (16.8 to 16.4%). Bernardino soils generally have greater grass cover (13.7%) than Hathaway soils (12.1%) although the total cover (16.8 to 16.3%) is only slightly greater.



		% frequency
Boch	Bouteloua chondrosioides	20.0
Bogr	Bouteloua gracilis	10.0
Bohi	Bouteloua hirsuta	15.7
Hibe	Hilaria belangeri	43.0
Arsp	Aristida spp.	27.7
Boer	Bouteloua eriopoda	75.0
Caer	Calliandra eriophylla	20.7
Crco	Croton corymbulosus	32.0
Trmu	Tridens muticus	21.3
Trpu	Tridens pulchellus	20.3
Bouteloua curtipendula (not associated)		37.7

Fig. 2. Statistically significant positive associations among major plant species. Frequency represents the percentage of 3-m intervals in which a species occurred.

The community dominated by *B. eriopoda* Torr. (black grama) included the two major nongrass species and was found primarily on SE to SW aspects, particularly on upper slopes. It was generally re-

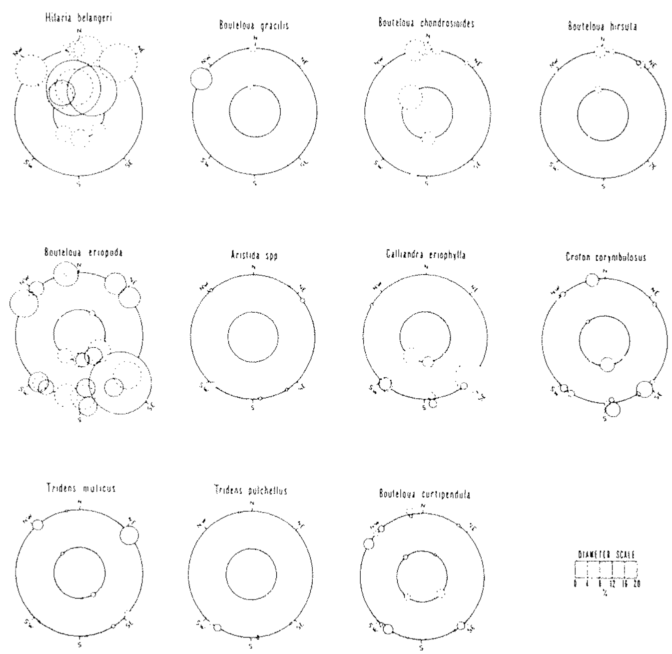


Fig. 3. Percent plant cover for 30 intercepts as a function of aspect, slope position, and soil series. The inner and outer circles for each species represent lower and upper slopes, respectively. Solid and broken line circles represent intercepts on Hathaway and Bernardino soils, respectively. The plotted circle diameter is proportional to percent cover. Intercepts with < 0.5% cover for a particular species are excluded.

stricted to upper slopes of Hathaway soils when it did occur on the northern aspects (Fig. 3). The community dominated by *Hilaria belangeri* (Steud.) Nash (curly-mesquite) was found primarily on NE to NW aspects, particularly on Bernardino soils. It was generally restricted to lower slopes when it did occur on Hathaway soils.

The percent plant cover of most species varies with aspect, soil series, or slope position (Fig. 3). Several species of *Aristida* (three-awn) occurred on the study area. The most common were probably *A. arizonica* Vasey, *A. longiseta* Steud., and *A. pansa* Woot. and Standl. The genus was rather evenly distributed, but was more common on

Hathaway soils. *Bouteloua eriopoda* was found primarily on upper slopes and on SE to SW aspects. Upper NE to NW exposures were well represented, but mainly on Hathaway soils. *Calliandra eriophylla* was dominant on SE to SW aspects with both soil types and slope positions well represented. *Croton corymbulosus* was found on all aspects, but somewhat more on the SE to SW, and mainly on Hathaway soils. All aspects, but particularly NE to NW, were also represented by *Tridens muticus* (Torr.) Nash, and almost exclusively on Hathaway soils. *T. pulchellus* (H.B.K.) Hitch. was mainly found on SW to SE exposures, but was not present on lower slopes. *Bouteloua chondrosioides* (H.B.K.) Benth. (spruce-top grama) was found only on Bernardino soils and mainly on NW to NE aspects. *B. gracilis* (H.B.K.) Lag. (blue grama) was represented exclusively on NW and N exposures, and particularly on upper slopes. Upper NE to NW aspects had the greatest percent cover from *B. hirsuta Lag.* (hairy grama), particularly on Bernardino soils. *Hilaria belangeri* was dominant on NE to NW exposures, but was found on Hathaway soils almost exclusively on lower slopes. Only the lower slopes with Bernardino soils had a significant representation on SW to SE aspects. *Bouteloua curtipendula* was ubiquitous, but was not positively associated with any other species.

SOILS: Means for soil variables were plotted by aspect, slope position, and soil series (Figs. 4 and 5) based upon 90 soil samples each from the crust and at the 0- to 15-cm depth. Data for NE Bernardino and SW Hathaway soils on lower slopes were unavailable because representative homogeneous study sites were not found. A series of one-way analyses of variance was performed on both crustal and 0- to 15-cm samples, grouping data by either aspect, slope position, or soil series, although the unavailable data resulted in a less precise analysis.

Slope position.—Only values for silt (F=1%) from upper slopes and clay (F=5%) from lower slopes at the 0- to 15-cm depth and organic carbon (F=5%) from lower slope crustal samples, were significantly greater, based upon the slope position analysis.

Aspect.—Because of the more acid Bernardino soils, the pH on the N aspect for 0- to 15-cm samples was significantly less than values from all other aspects, while the crustal pH was significantly less than values from all except NW, based upon Duncan's New Multiple Range Test at the 5% level (Li, 1964). Similar tests indicated that 15 atm moisture retention at the 0- to 15-cm depth from the SE aspect was

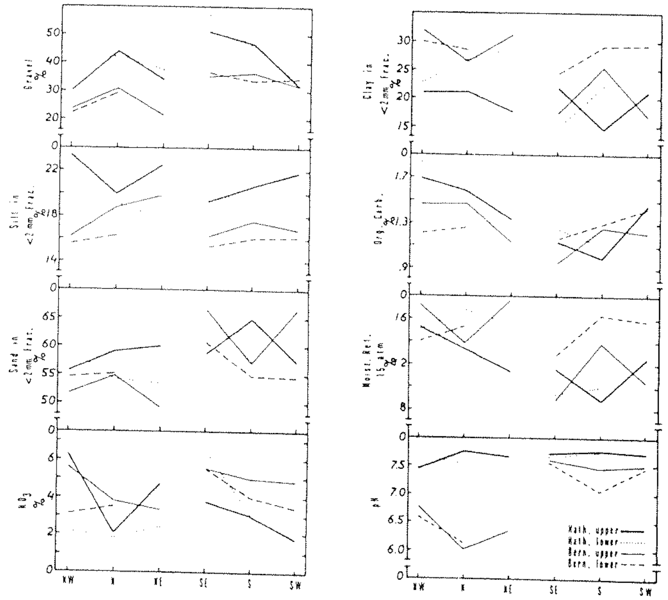


Fig. 4. Soil variables from 0- to 15-cm samples as a function of aspect, slope position, and soil series.

significantly less than values from N and NW aspects and that values from NW, N, and NE exposures were significantly greater than from S and SE for organic carbon at 0- to 15-cm. The percent gravel at 0- to 15-cm was also significantly greater from the SE aspect than from the NW, NE, and SW.

Soil series.—Bernardino soils at 0- to 15-cm had significantly greater moisture retention at 15 atm (F=1%) and clay content (F=1%) and significantly lower pH (F=1%), silt content (F=1%), and percent gravel content (F=1%) than Hathaway soils. Crustal Bernardino soils also had a significantly lower pH (F=1%) than Hathaway soils, but the gravel content (F=1%) was significantly greater, the converse of 0- to 15-cm samples. Nitrate (F=5%) was significantly greater from crustal Hathaway soils.

The lower pH on Bernardino soils, particularly evident on NW to

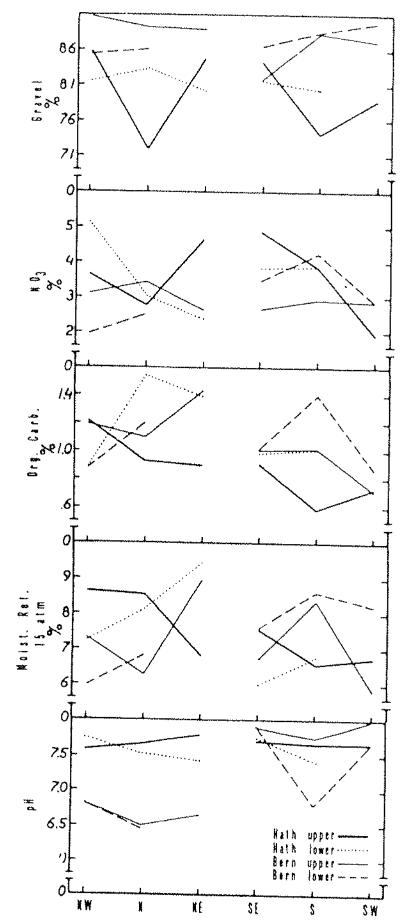


Fig. 5. Soil variables from crustal samples as a function of aspect, slope position, and soil series.

NE aspects (Figs. 4 and 5), indicates greater leaching and was probably related to the relatively low incident radiation of these exposures during the winter rainy season. The greater clay content and moisture retention at 15 atm on Bernardino soils indicate that more clay may be formed from Bernardino than Hathaway parent material and that some of the B horizon has been included in the 0- to 15-cm sample. Aspects from SE to SW generally had relatively low moisture retention and clay content, but an interesting exception was a Bernardino soil on a lower slope. A combination of plant species and increased lower slope runoff may partially account for this exception. Causes for the lower silt content on Bernardino soils and lower slopes are unknown. Also unknown are the causes for greater percent gravel on Hathaway 0- to 15-cm samples, but the opposite on crustal samples. A possible explanation may involve differences in soil formation because of variation in parent material. The generally lower values on SW to SE aspects for moisture retention and organic carbon, but higher gravel content, agree with the findings of Klemmedson (1964).

Soil correlations.—Correlation coefficients were obtained for soil variables based upon 90 comparisons for each correlation (Table 1). A positive correlation between 0- to 15-cm and crustal samples for the same variable was significant for moisture retention, organic carbon, and particularly for pH, but was insignificant for nitrate. A significant negative correlation occurred for gravel content. No significant correlation was found between nitrate at 0- to 15-cm and any other soil variable. Crustal nitrate was significantly correlated only with the 0- to 15-cm gravel and the crustal moisture retention. This is probably indicative of the transient nature of soil nitrate or the difficulty of its accurate measurement, or both. Moisture retention was significantly correlated with all other variables except nitrate and silt. The most obvious grouping of soil variables is a high moisture retention, organic carbon, clay content and crustal gravel with low pH, sand content and 0- to 15-cm gravel. The converse grouping is also obvious.

SOIL-PLANT RELATIONS: Plant cover data from 90 line intercepts were correlated with soil variables from corresponding soil samples (Table 2). Although plant cover is not an ideal measure of species significance in an ecosystem, it was considered the best vegetation variable available. Importance value could have been utilized, but each isolated intercept would require consideration as an individual plant because vegetative reproduction is extensive, making a realistic

TABLE 1

Correlation coefficients for 13 soil variables. $P<.01 = .267$ and $P<.05 = .205$. Decimal points are omitted.

	Variables	Crustal soil: Gravel	pH	Nitrate	Organic carbon	Moisture retention	0-15 cm soil layer: Sand	Clay	Silt	Gravel	pH	Nitrate	Organic carbon	Moisture retention
0-15 cm soil layer	Moisture retention	41	-42	-14	60	53	-76	79	-17	-67	-36	05	66	
	Organic carbon	16	-16	04	35	30	-51	40	17	-16	-17	02		
	Nitrate	20	07	08	06	08	12	-07	-09	-01	-02			
	pH	-39	88	14	-25	17	38	-48	28	42				
	Gravel	-25	31	35	-10	-03	45	-45	05					
	Silt	-25	-29	06	-12	07	-10	-36						
	Clay	36	-54	-08	47	26	-89							
	Sand	-26	44	06	-44	-31								
Crustal soil	Moisture retention	23	07	22	62									
	Organic carbon	46	-37	04										
	Nitrate	-06	10											
	pH	-37												
	Gravel													

TABLE 2

Correlation coefficients for percent plant cover and 13 soil variables. $P<.01 = .267$ and $P<.05 = .205$. Decimal points are omitted.

Species	0-15 cm soil layer: Moisture retention	Organic carbon	Nitrate	pH	Gravel	Silt	Clay	Sand	Crustal soil: Moisture retention	Organic carbon	Nitrate	pH	Gravel
Aristida spp.	-14	-08	18	19	03	26	-25	14	-10	-30	06	25	-08
Bouteloua eriopoda	-28	-26	26	48	20	02	-30	31	22	-08	07	47	-09
Calliandra eriophylla	-16	-27	-01	21	02	02	-11	10	05	-03	03	18	-06
Croton corymbulosus	-25	-19	-21	12	16	04	-27	27	-02	-18	-01	25	-21
Tridens muticus	-19	05	18	21	24	04	-28	28	-09	-09	56	16	-06
T. pulchellus	-14	02	-22	22	-03	22	-14	04	-03	-17	-14	15	-04
* consensus	-	-		+	+	+	-	+	+	-	+	+	-
Bouteloua chondrosioides	10	01	-02	-64	-16	-16	22	-16	-17	06	-09	-55	28
B. gracilis	09	12	02	-03	-06	23	-02	-09	06	07	-10	-01	13
B. hirsuta	07	-03	05	-47	-29	-03	08	-08	-12	03	-06	-35	13
Hilaria belangeri	59	43	-21	-46	-22	-33	63	-51	10	36	-13	-46	21
* consensus	+	+	-	-	-		+	-		+		-	+
Bouteloua curtipendula	-09	-15	-03	08	-05	13	-22	17	-04	-15	-09	16	04

* Consensus based only on statistically significant correlation coefficients.

determination of an individual plant impractical. The many (1–2 cm) intercepts found for plants such as *Hilaria belangeri*, which greatly increase relative density, are a doubtful measure of their importance when compared to the many larger intercepts for plants such as *Bouteloua eriopoda* which result in a comparatively small relative density.

In terms of the number of significant correlations found between species plant cover and soil variables, the most important soil factors are pH and clay content (Table 2). The species in Table 2 were grouped according to the association pattern found from the coefficient of interspecific association (Fig. 2). Soil-plant correlations support this association. Statistically significant correlation coefficients which are positive between species and soil variables in one association are negative in the other, or the converse. The only exceptions are silt and nitrate from the 0- to 15-cm depth and crustal nitrate. Nitrate was previously found to lack correlation with other soil variables while silt was correlated with only three others (Table 1).

Within the range of the soil variables measured, it was concluded that the community dominated by *Bouteloua eriopoda* was found primarily on 0- to 15-cm soils of lower moisture retention, organic carbon and clay content, but higher pH, gravel, and sand content. The converse was indicated for the community dominated by *Hilaria belangeri*. Although crustal pH and organic carbon were similar to values at the 0- to 15-cm depth, the pattern was the opposite for crustal gravel content. It may be concluded that the *Bouteloua eriopoda* community was found primarily on upper Hathaway soils from SW to SE aspects while the *Hilaria belangeri* community was found primarily on Bernardino soils from NW to NE. Such a generalization has limited value, however, because of the wide variation in species distributions (Fig. 3). Although factor interaction is obviously complex, some soil variables were more highly correlated with some species than with others (Table 2). Changes in 0- to 15-cm and crustal pH are factors most related to the changes in plant cover for *Bouteloua chondrosioides*, *B. eriopoda*, and *B. hirsuta*; however, for *Hilaria belangeri* they are clay content and moisture retention.

Although incident solar radiation was not measured, it is felt to be an important cause of the variation in microclimate, soil, and vegetation on the different aspects. Total annual direct beam solar irradiation at 30° N latitude and 20% slope is greatest on S aspects (Fons, Bruce, and McMasters, 1960). Exposures on the SW or SE receive 98.9%, NW or NE 86.5%, and N 82.5% of the average annual total for the S aspect. These relative values vary considerably with the time of year. On 21 December, irradiation is still greatest on S aspects, with SW or SE receiving 92.3%, NW or NE 55.1%, and N only 47.3% of S. The order is reverse on 21 June when irradiation is greatest on N aspects with NW or NE receiving 99%, SW or SE 94.3%, and S 93.3% of N. These theoretical relative values may be modified because of variation in morning and afternoon cloud cover, particularly on NE, SE, NW, and SW aspects. Nearly all growth of perennial grasses takes place during the summer rainy season of July, August, and part of September (Humphrey, 1958) when the mean theoretical irradiation is nearly equal on all aspects included in this investigation. Although cloud cover data are not available at or near the study area, data for Tucson, Arizona, approximately 70 mi. NW, indicate that afternoon exceeded morning cloud cover for July, August, and September by an average of 30% over a 9-year period (Sellers, 1958). It seems fair to assume that cloud cover is greater in the afternoon than in the morning during the summer growing season in Tombstone also, since the amount of summer rain is greater than in Tucson and has the same moisture source in the Bermuda High. Although irradiation may be greatest on NW–SW aspects during the warmest time of the day, there is little doubt that these aspects receive less total daily irradiation than NE–SE. A NW exposure in particular would be affected by afternoon cloud cover because the sun sets near and radiates most directly there during the summer. However, many significant differences between soil variables and plant cover were found from NW–NE to SW–SE, rather than from NW–SW to NE–SE, indicating the probable importance of irradiation differences other than during the summer growing season.

The effects of grazing on species distribution were difficult to evaluate. *Hilaria belangeri* may actually increase under grazing pressure (Canfield, 1948). Although opposing aspects were equally available, utilization by cattle was apparently heavier on the S than on the N aspect, particularly during the late winter months when growth of perennial grasses was more retarded on the N (Cumming, 1951). However, grazing may be heavier on the N aspect following the summer rainy season because grasses remain green longer on the N.

Growth of perennial grasses is inconspicuous during the winter rainy season and apparently is limited by low temperatures (Humphrey, 1958), although other factors, including photoperiodism and low soil moisture, may also be limiting. *Hilaria belangeri* and perhaps other species in its community appear to be limited on SW to SE aspects because the greater irradiation, other than during the summer rainy season, causes drought conditions which reach critical proportions sooner in the arid spring or fall. The generally lower soil moisture retention of SW to SE aspects would also tend to bring about critical drought conditions sooner in a drying soil. When species of the *H. belangeri* community were found on SW to SE aspects, they were almost exclusively on Bernardino soils of lower slopes. Lower Bernardino soils were previously shown to be significantly higher in moisture retention and clay content than other SW to SE soil positions. Lower slopes also benefit from the substantial runoff from upper slopes, and may be blocked from some early morning or late afternoon solar radiation by the upper slopes of an opposite aspect. Cold air drainage may result in lower air temperatures and evapotranspiration on lower slopes.

It is tempting to suggest that species of the *Bouteloua eriopoda* community were limited on NW to NE aspects because they were unable to compete with plants of the *Hilaria belangeri* community, but such a contention requires further investigation.

We gratefully acknowledge the assistance of Raymond Brown in obtaining field samples and Loel Cooper, Virginia Slate, Juanita Valenzuela, John Urquhart in soil analysis. Raymond M. Turner, Kenneth G. Renard, and Willard Van Asdall kindly reviewed the manuscript. Computer facilities were provided by the University of Arizona Computer Center.

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